Creating and Accelerating Flat Bunches in the LHC

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CARE-HHH Workshop 2008

Scenarios for the LHC upgrade and FAIR

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- SPS Experiments/Discussions
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- PS Experiment/Discussions
  - Heiko Damerau, Steven Hancock, Edgar Mahner, Fritz Casper

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Outline

- Motivation
- Introduction
  - Flat-bunch scheme in LHC luminosity upgrade- why?
  - Short history
- Flat bunch creation and Acceleration
- Recent efforts at CERN
  - Beam studies in SPS and PS
- Prospects at LHC
  - Possibly benefit even in early operations
- Conclusions

Motivation

- F. Ruggiero and Frank Zimmermann have shown that one can increase the LHC luminosity by $\sqrt{2}$ (!!) for the same number of particles and the same total beam-beam tune shift, **by simply flattening** the bunches.

  ← Increasing the Piwinski angle $\phi = \theta_c \sigma_z / (2\sigma^*_x)$ (hence LPA-scheme)

- Flat bunches of antiproton have been successfully created and are used in daily operation in the Fermilab Recycler.

Hence the interest in flat bunches in LHC !

Merits and Issues with Large ϕ

During the CARE-HHH 2007 workshop the advantages and problems are discussed. I am simply recalling a few of them here.

- Merits
  - No elements in the detectors
  - Lower Chromaticity
  - Less e-cloud issues
  - Less demands on the IR quadrupoles

Last week there was a workshop dedicated to addressing the e-cloud issues in LHC

- Challenges
  - Flat bunch production and Acceleration
  - High bunch charges (?)
  - A few ohers ..

Present LHC Upgrade Path

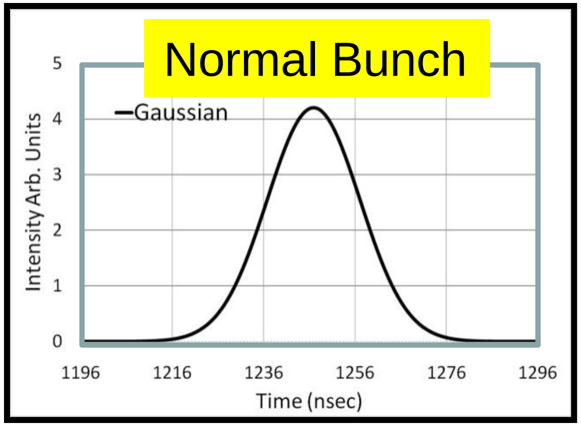
F. Zimmermann et al.

Parameter		Nominal	Ultimate	ES & FCC	LPA
bunch intensity	10^{11}	**1.15**	**1.7**	**1.7**	**4.9**
transv. emitt.	μm	3.75	3.75	3.75	3.75
bunch spacing	ns	25	25	**25**	**50**
beta* at IP1&5	m	0.55	0.5	0.1	0.25
crossing angle Piwinski parameter	μrad	285 0.64	315 0.75	0 0	381 2
peak lumi $\mathscr{L}$ average $\mathscr{L}$ (turnaround time 10h)	10^{34} $cm^{-2}s^{-1}$	1.0 0.46	2.3 0.91	**15.5** **2.4**	**10.7** **2.5**
event pile-up		19	44	294	403

Note that for ES and FCC scheme the β^* is 0.1m

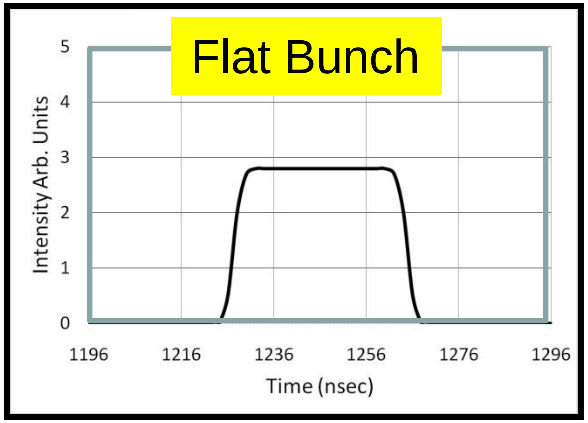
Flat bunch creation

- Bunches with uniform or nearly uniform line-charge distribution are “Flat Bunches”



Transform

Preserving the Intensity & Emittance.

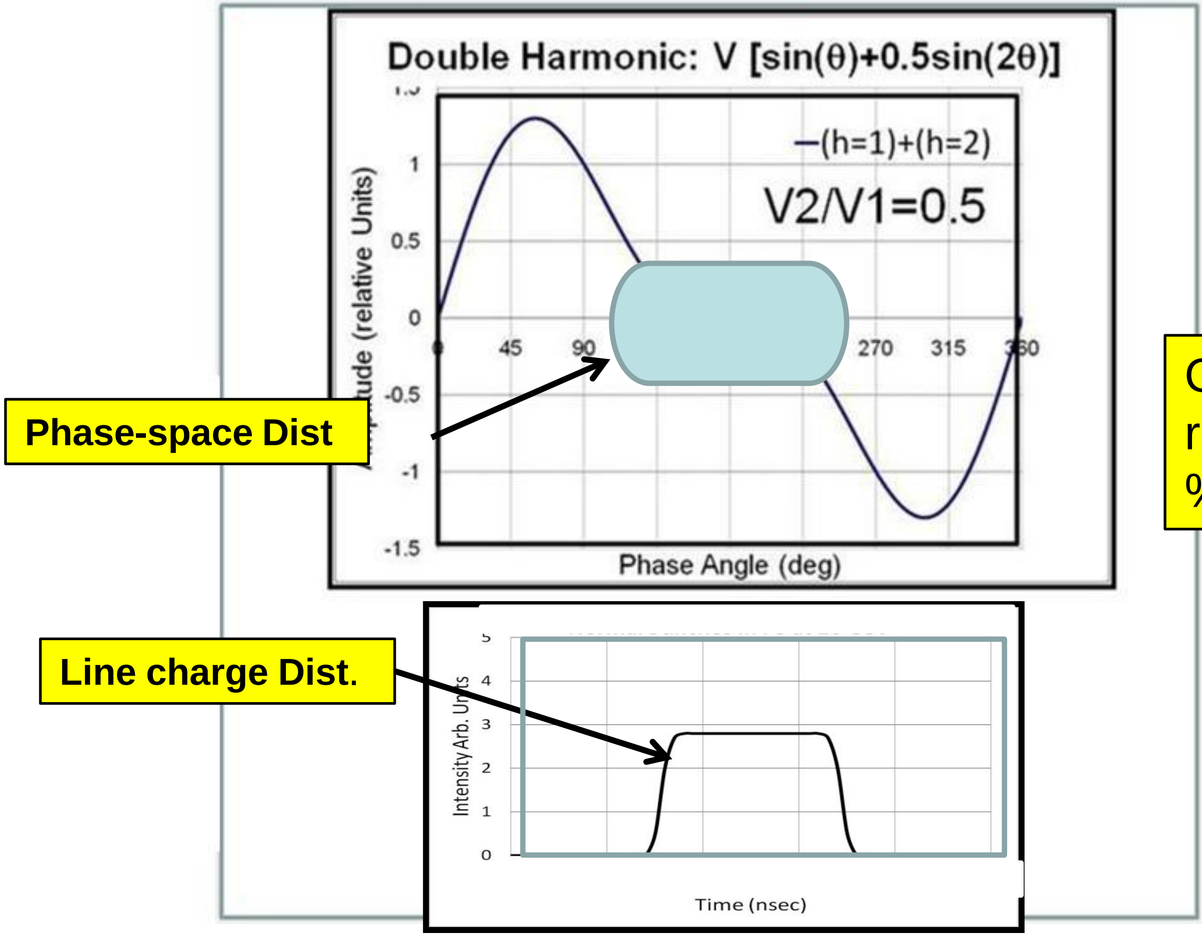


- There are several ways to create flat bunches
  - Using resonant rf system
    - Double, triple or multiple harmonic rf system
    - Longitudinal hollow bunches, Carli’s technique
  - Barrier rf to generate Flat bunches
    - Fermilab Recycler Flat bunches
    - Flat bunches at KEK

Flat bunches with Double Harmonic RF

- References
  - 2nd Harmonic debuncher in the LINAC, J.-P. Delahaye et. al., 11th HEACC, Geneva, 1980.
  - Empty Bucket deposition in debunched beam, A. Blas, et, al.,EPAC2000 p1528
  - Beam blowup by modulation near synchronous frequency with a higher frequency rf, R. Goraby and S. Honcock, EPAC94 p 282
  - Creation of hollow bunches by redistribution of phase-space surfaces, C. Carli and M. Chanel, EPAC02, p233.
  - RF phase jump, J. Wei et. al. (2007)
  - Diagnosis of longitudinal instability in the PS Booster occuring during dual harmonic acceleration, A.Blas et. al., PS/ RF/ Note 97-23 (MD).
  - And more

Double harmonic rf system for flattening the bunches



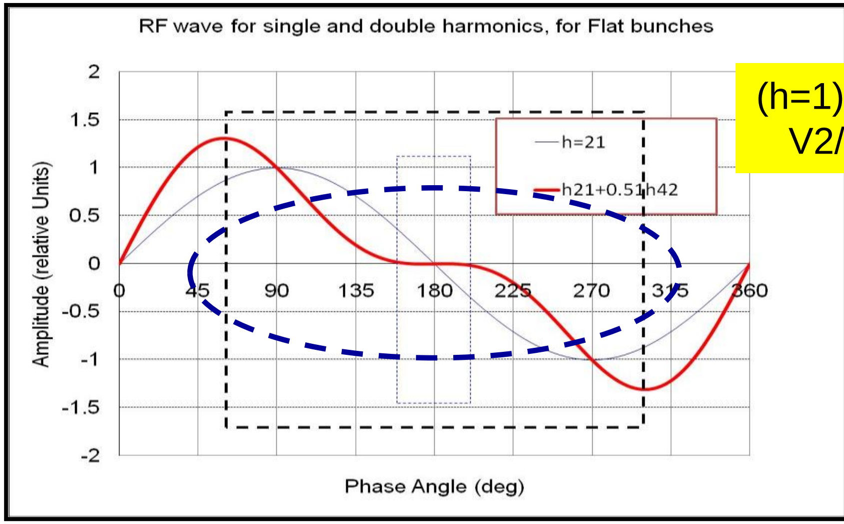
One can have the ratio V2/V1 a few % higher (<4%)

Flat-Bunches: If the phase angle between two rf system is 180^0 at the center.

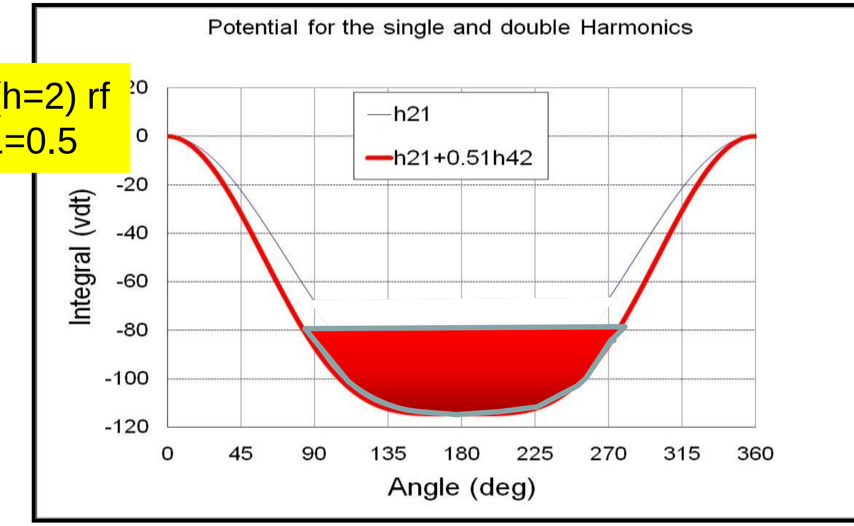
Short-Bunches: If this angle is 0^0.

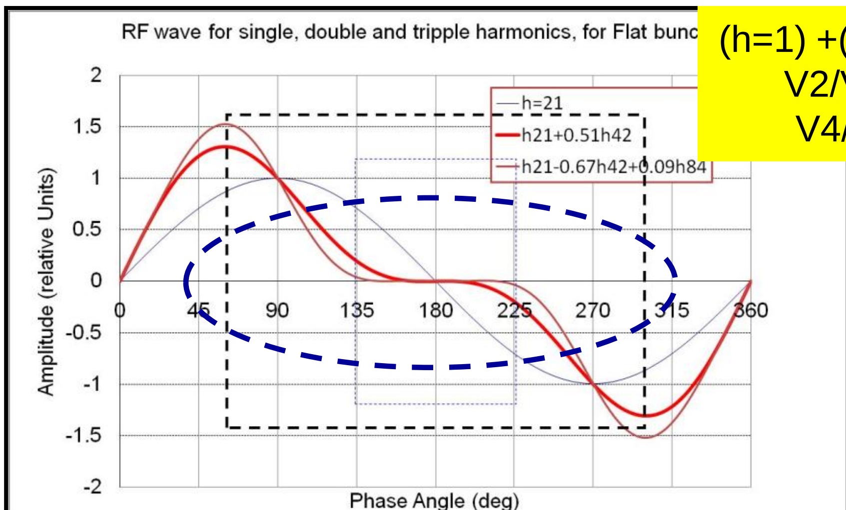
Triple Harmonic RF for Flatter Bunches

(wave forms & Integral(Vdt))

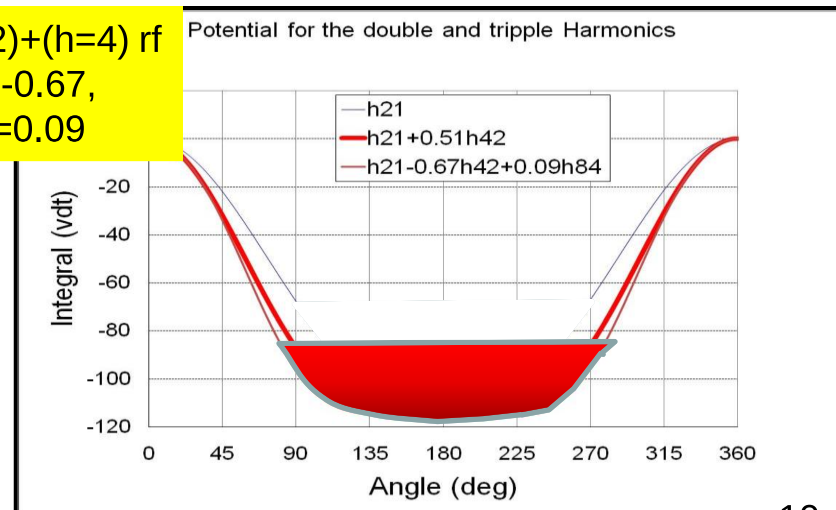


(h=1) +(h=2) rf
V2/V1=0.5





(h=1) +(h=2)+(h=4) rf
V2/V1=-0.67,
V4/V1=0.09



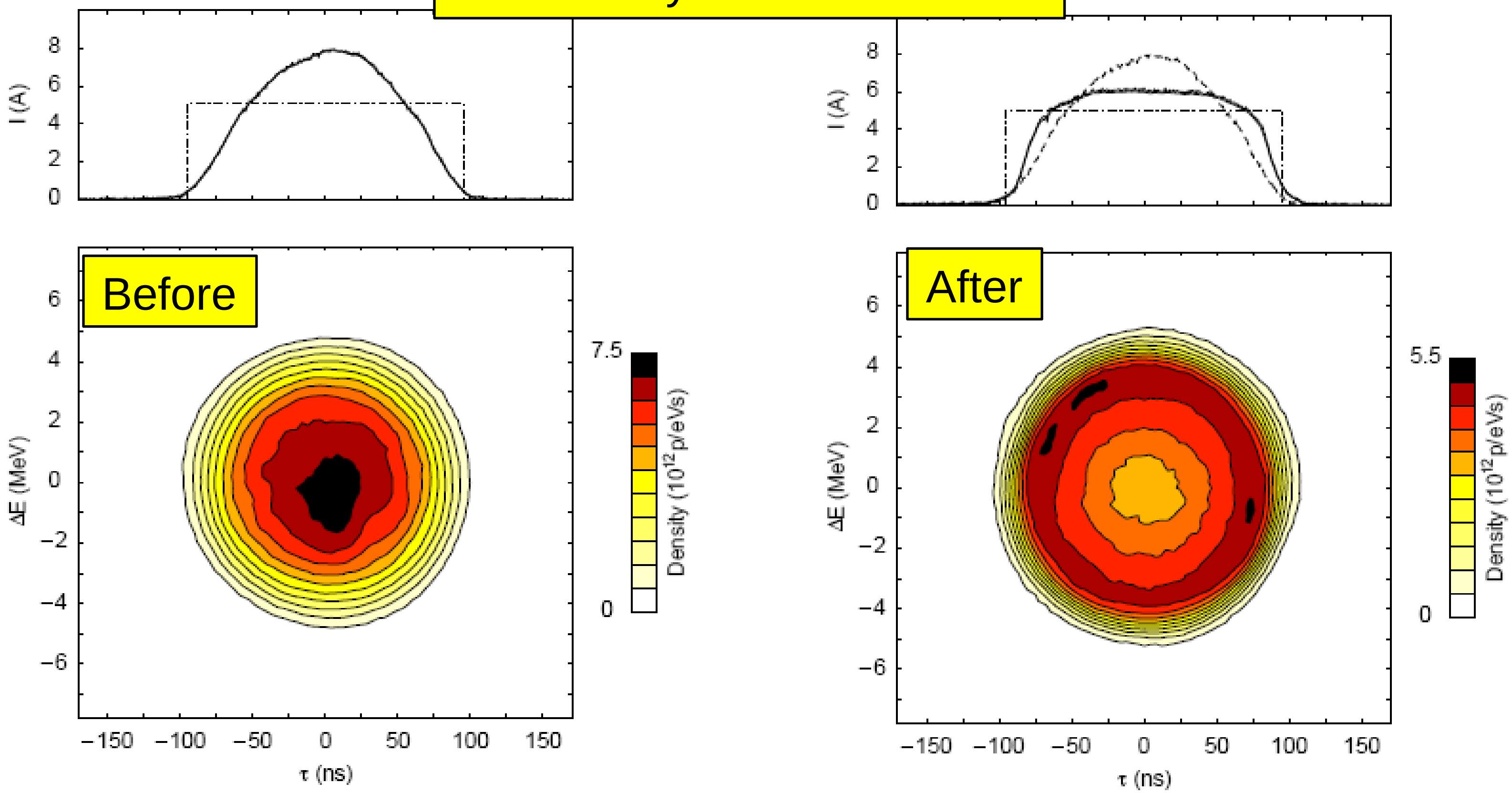
Carli's Hollow Beam Technique

(EPAC2002, p233)

Experimental Demonstration at CERN PSB

Beam Tomography : Before and After redistribution of phase-space

At intensity of **$6x10^{12}$/bunch**



The beam studies were carried out up to beam intensity of **$8x10^{12}$/bunch**

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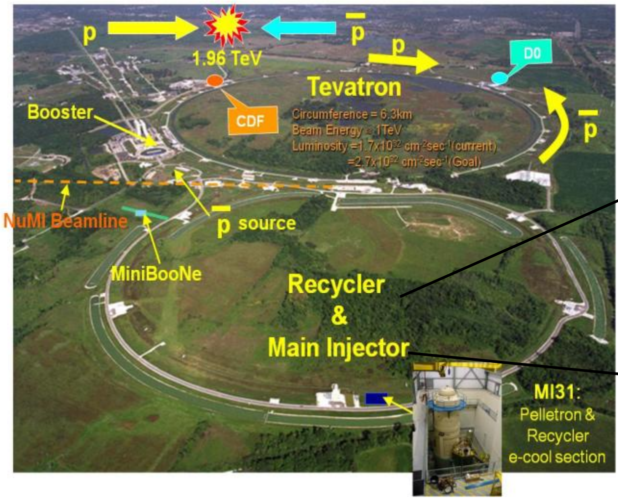
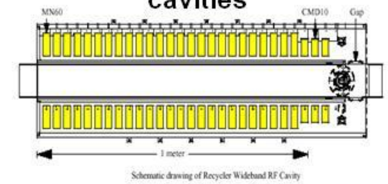
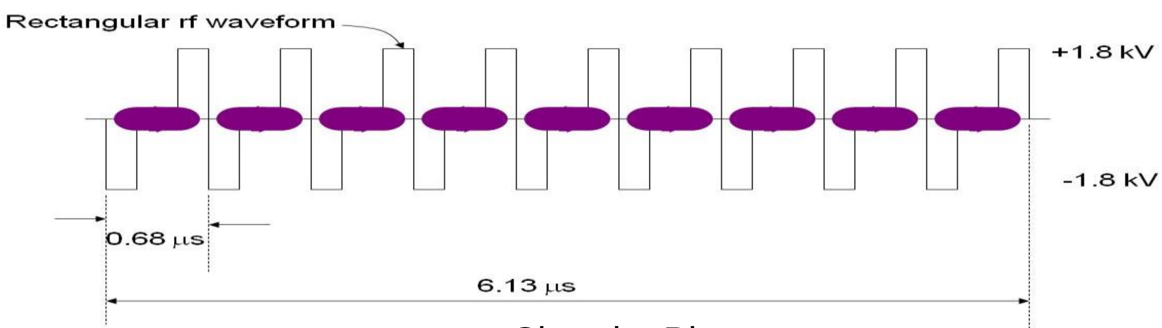
Barrier rf to generate flat bunches in the Fermilab Recycler



Recycler Barrier RF cavities



Schematic of the RF profiles for the flat beam in the RR



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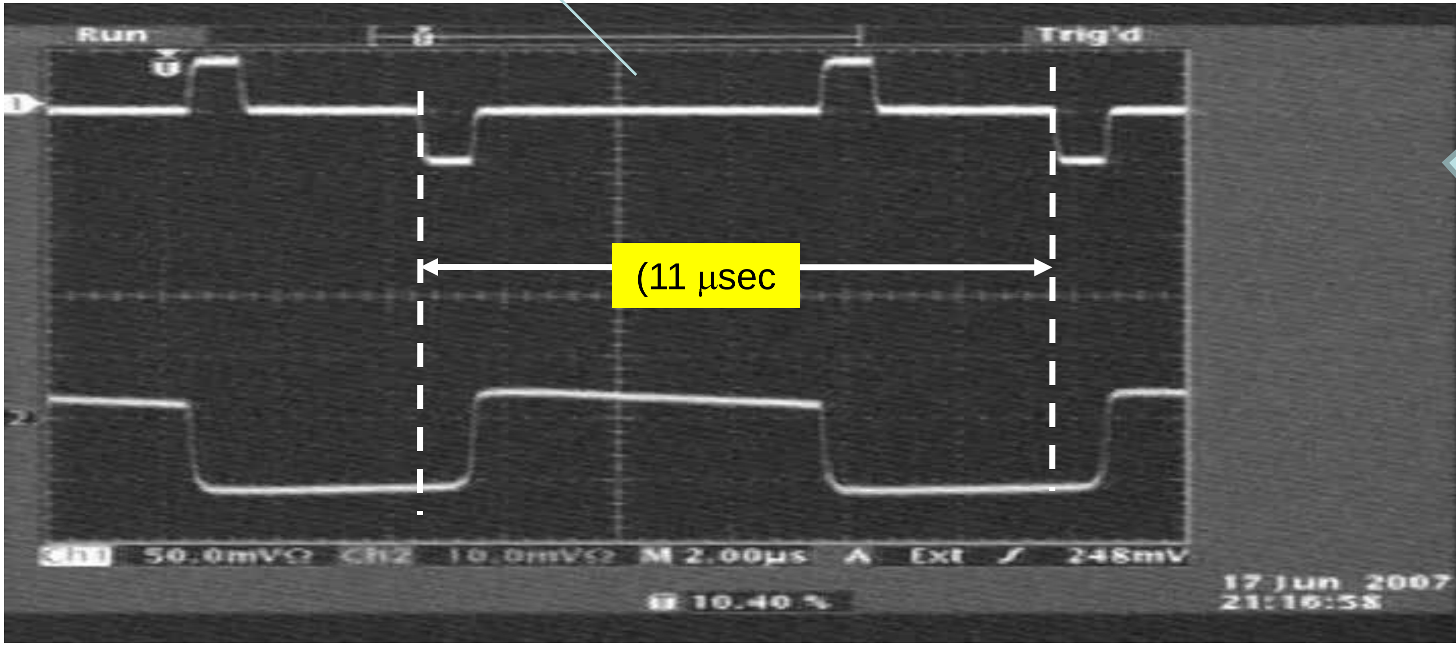
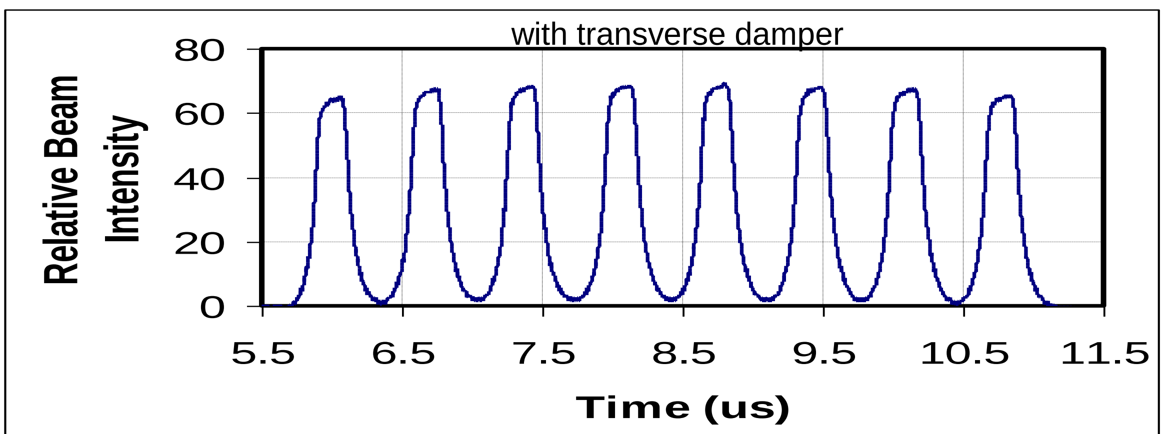
Barrier rf to generate flat bunches Fermilab Recycler



Video



Transverse Resistive wall Stability Threshold

Intensity = 4.2×10^{11}/ bunch

LE(95%) = 5 eVs

$<\varepsilon_T>$(95%) = 2.1 π-mm-mr

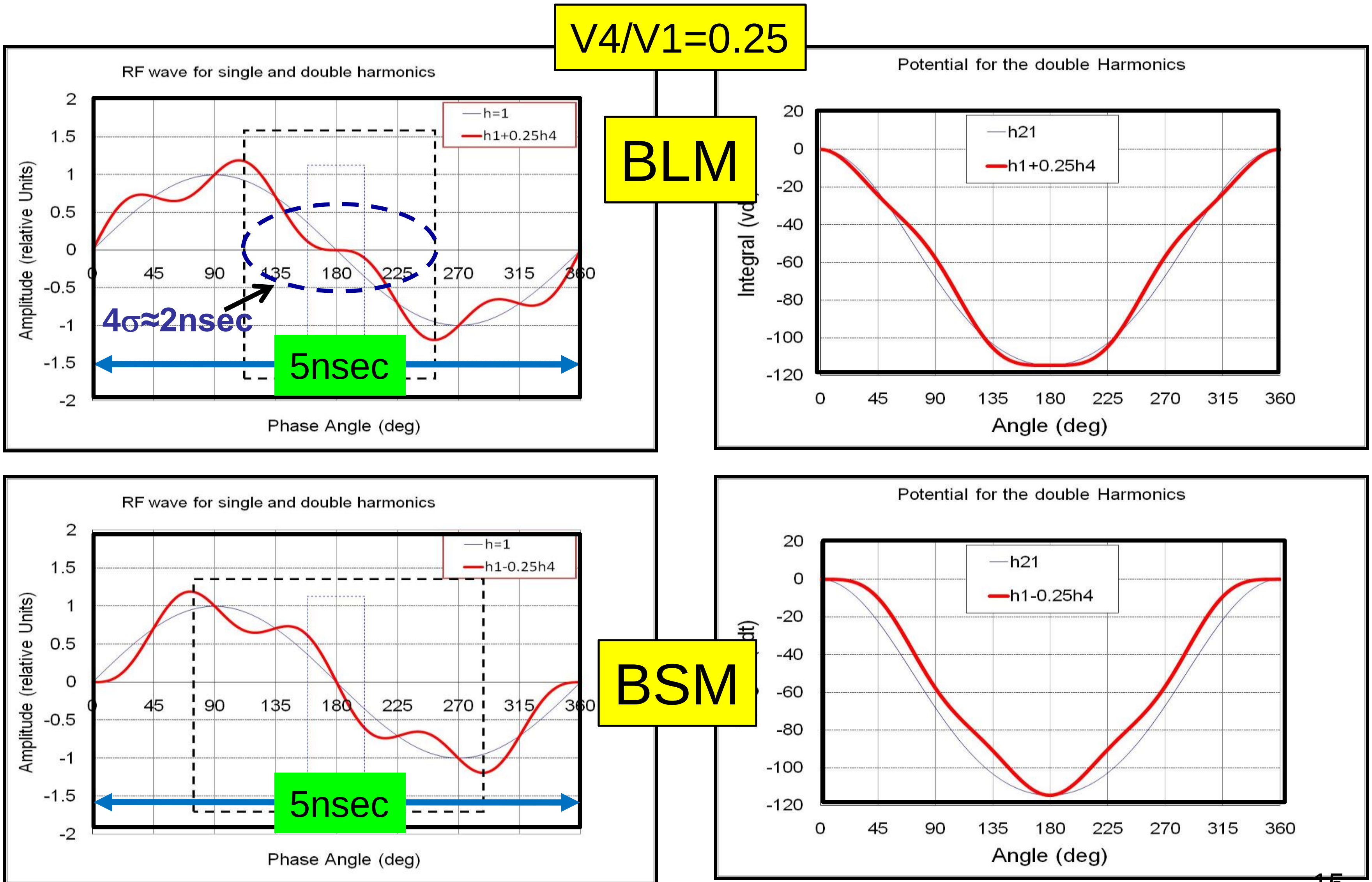
$$D = \frac{Npbar/10^{10}}{<\varepsilon_T(\pi\text{-mm-mr})>_{95\%} \cdot \mathrm{LE(eVs)}_{95\%}} \approx 4$$

SPS: Beam Studies with double harmonic rf

(E. Shaposhnikova,T. Bohl, T. Linnecar, J. Tuckmantel and C. Bhat)

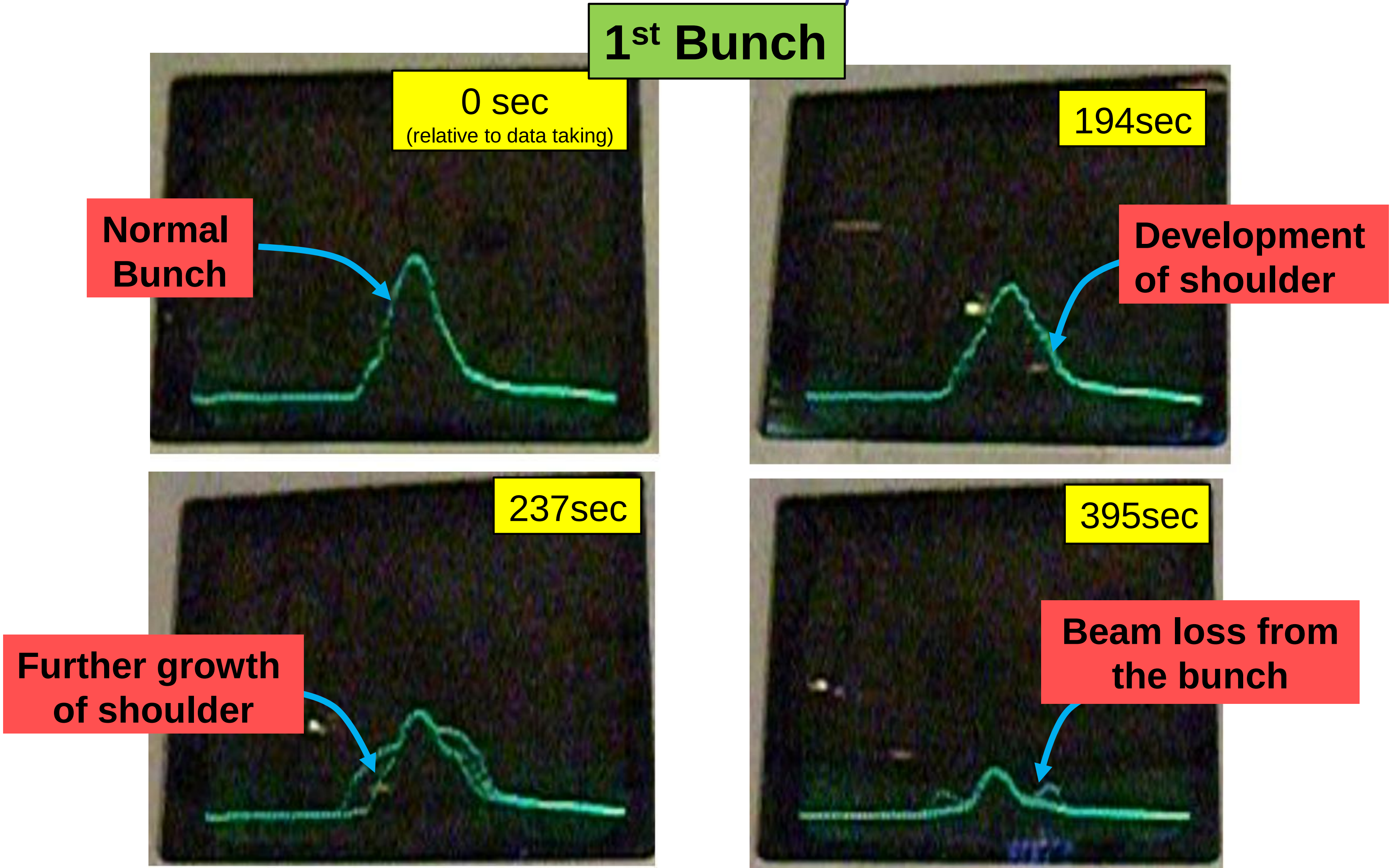
- During the last MD studies (Nov. 5, 2008), we have carried out beam studies in the SPS to revisit the beam instability issues in 200MHz+800MHz, (i.e., h=1+h=4) double harmonic rf system.
  ←During 2006 study (at 120GeV/c) development shoulder in bunches were seen (E. Shaposhnikova et. al.,)
- Studies were conducted under various conditions at 270GeV Flat top on a coasting beam
  - Four LHC type (intensity and Long. emitt.) bunches, separated by 550nsec
  - Different RF voltage ratios for V4/V1, **(V4(100-500kV), V1(1-3MV)**
  - Long. damper and Phase-loop ON and OFF
  - Bunch lengthening and shortening mode (BLM and BSM)

Double RF used in SPS Studies
(wave forms & Integral(Vdt)



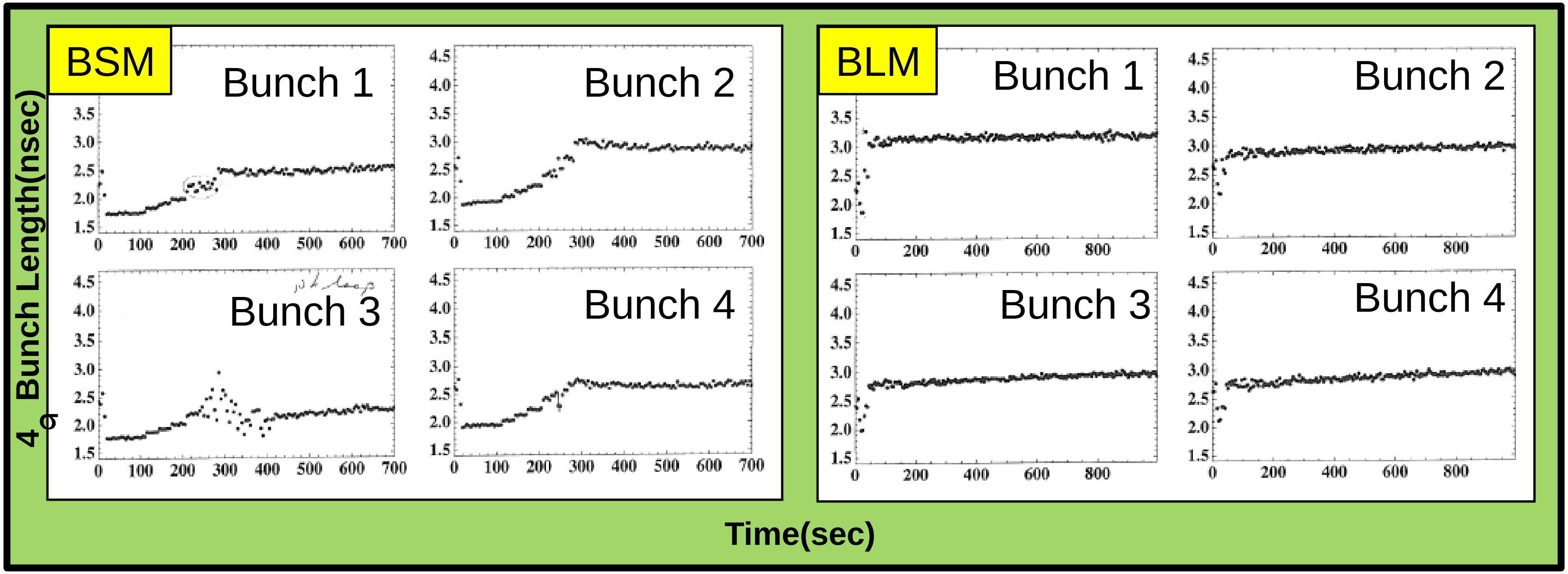
SPS Beam Studies(cont.): BLM

(a first look, Preliminary)
data from Nov. 5, 2008



SPS Beam Studies(cont.): BSM and BLM
(Preliminary)

- Both BSM and BLM scenarios showed beam blowup
- The instability kicked in between 0-350 sec.
- The order in which a bunch becomes unstable was quite random
- Even though initial bunch parameters are nearly the same, they stabilized at different bunch properties



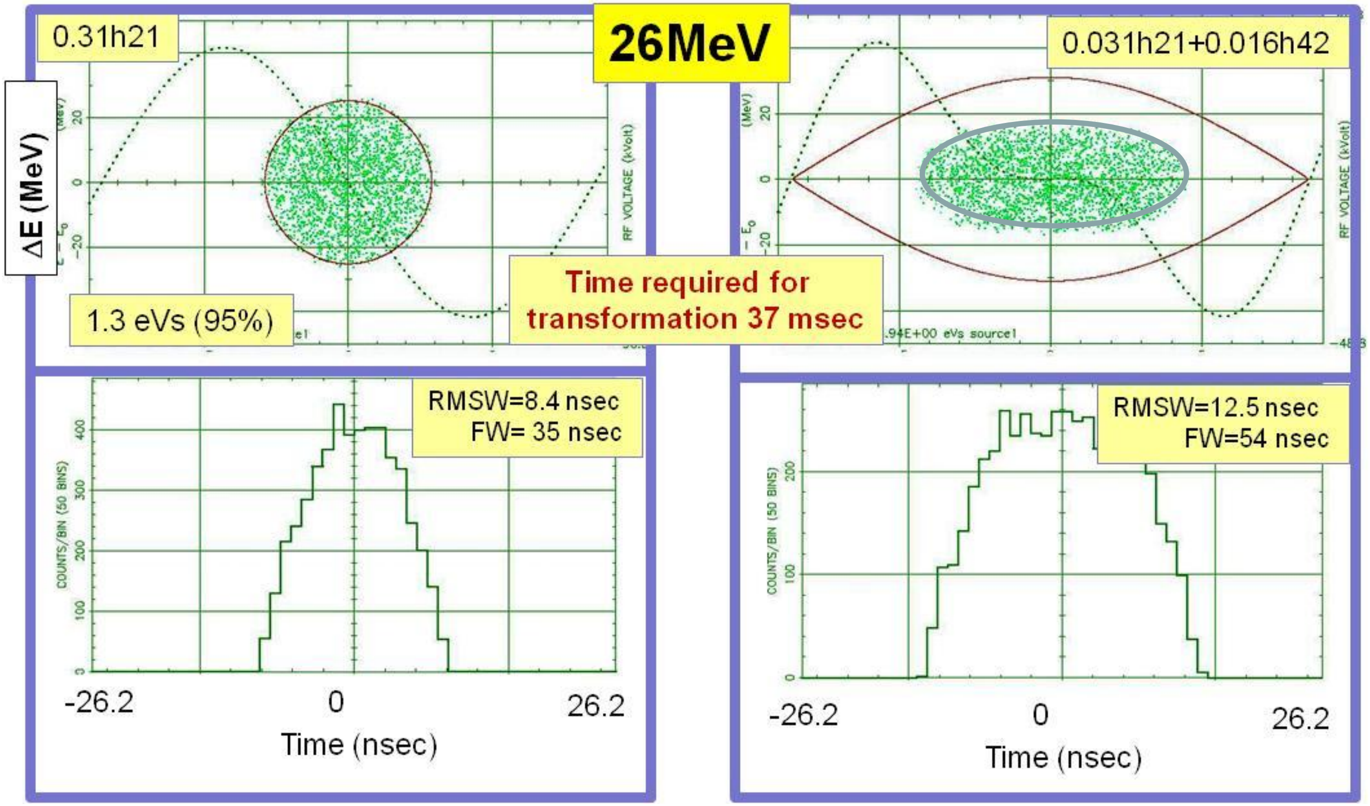
PS: Beam Studies with double harmonic rf

(C. Bhat, H.Damerau, S. Hancock, E. Mahner, F. Casper
and F. Zimmermann)

- Just before the end of the last MD period(Nov. 11, 2008), we have carried out beam studies in the PS using double harmonic rf to investigate the creation and stability of flat bunches.
  - These studies were motivated by beam dynamics simulations
  - Used h=21 and h=42 rf system
  - On the normal LHC beam acceleration cycle(LHC25) with nominal beam parameters
- After triple split at 1.4 GeV flat bottom, 18-bunches (1.4 eVs/each) are accelerated to 26 GeV. Then,
  - rf phase of h=42 is set to 180^0 relative to h=21 and V2/V1 is changed adiabatically from 0 to 0.51(≈0.016MV/0.031MV) in 35 ms.
  - Monitored the behavior of the bunches till the end of the cycle (~100ms).
  - Monitored e-cloud effect ← **No signal seen**

The phase and voltage ratio **V2/V1≈0.51** was a critical parameter in this study

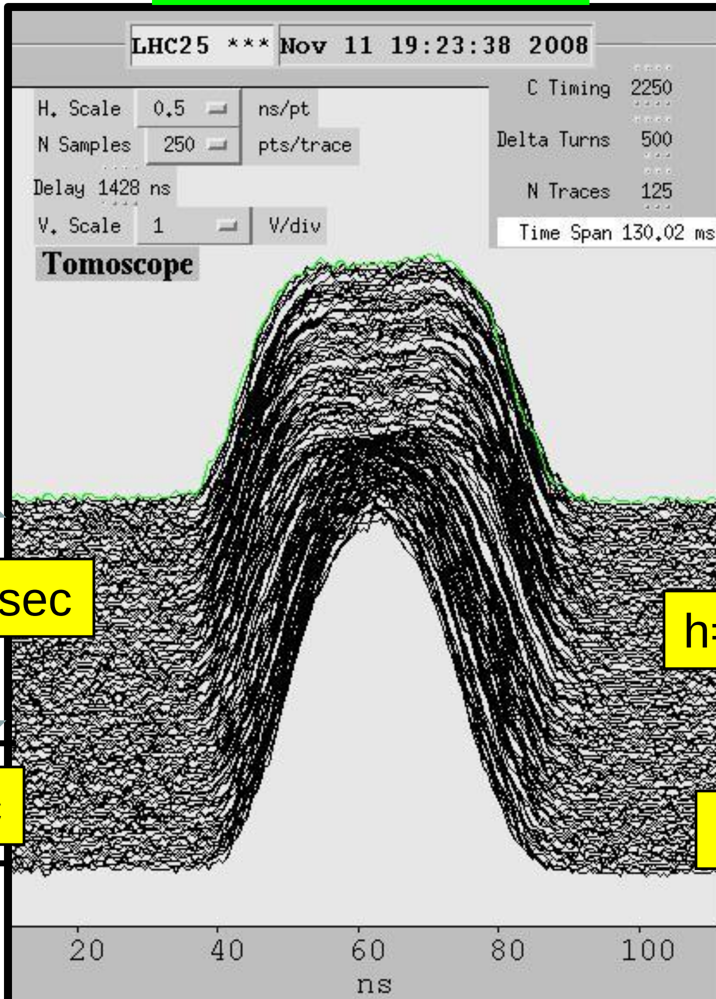
Evolution of RMSW of Bunches in PS while Flattening



Expected:-- About 50% increase in RMSW from beginning of rf manipulation to the flattened bunch

PS data from 081111-1924 and Simulation

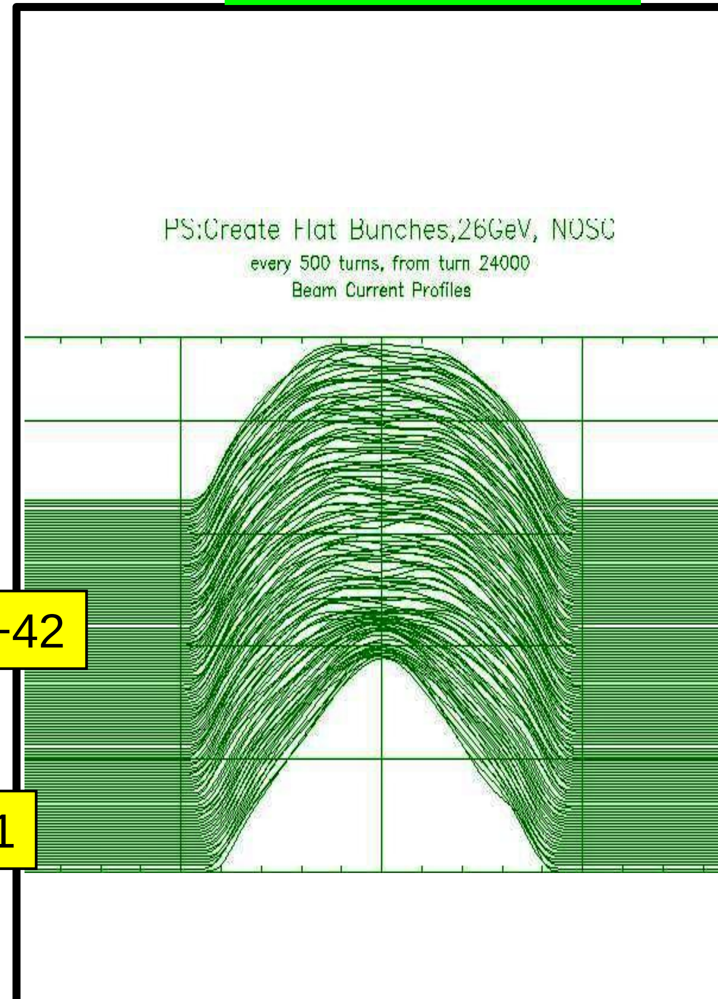
Experimental Data



95 msec

35 msec

ESME Simulation



h=21+42

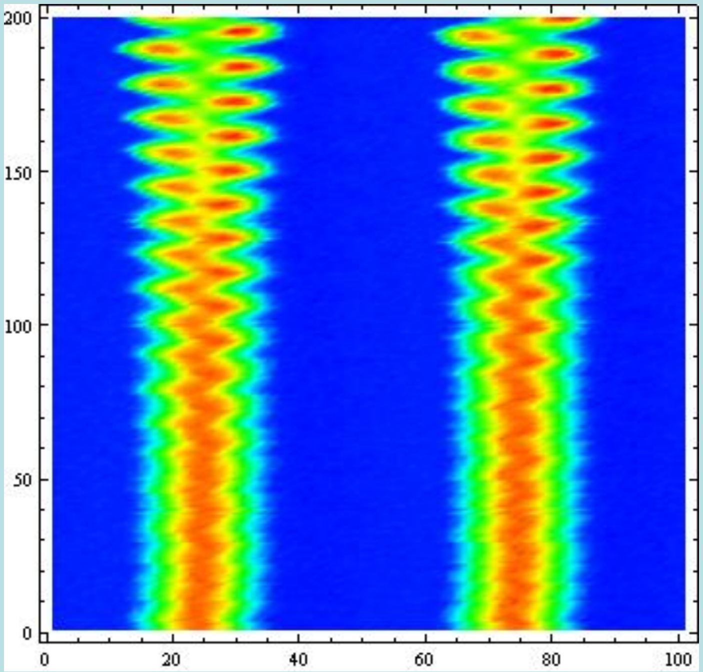
h=21

PS data from 081111

(Comparison between normal bunches with flat bunches)

Last two bunches

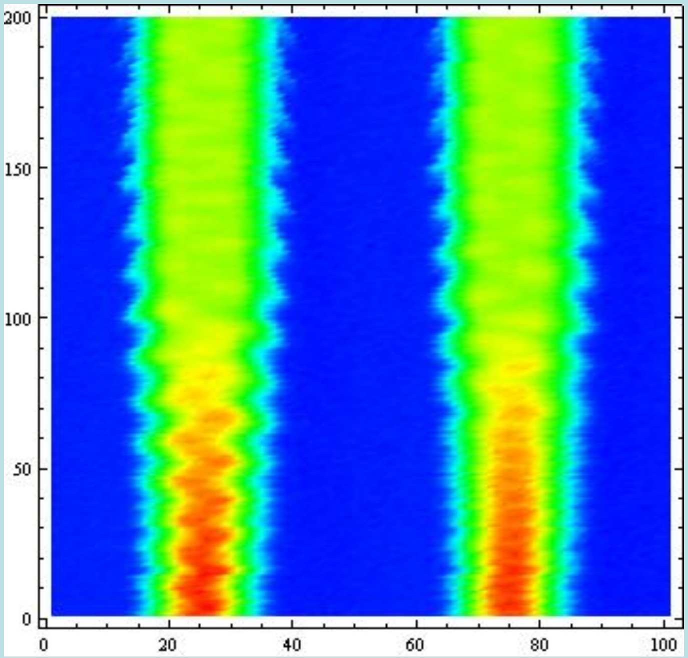
V(H21)=31kV,
Hereward damper off



Became
more unstable

☹

V(h21)=31kV, V(h42)=16kV
, Hereward damper off

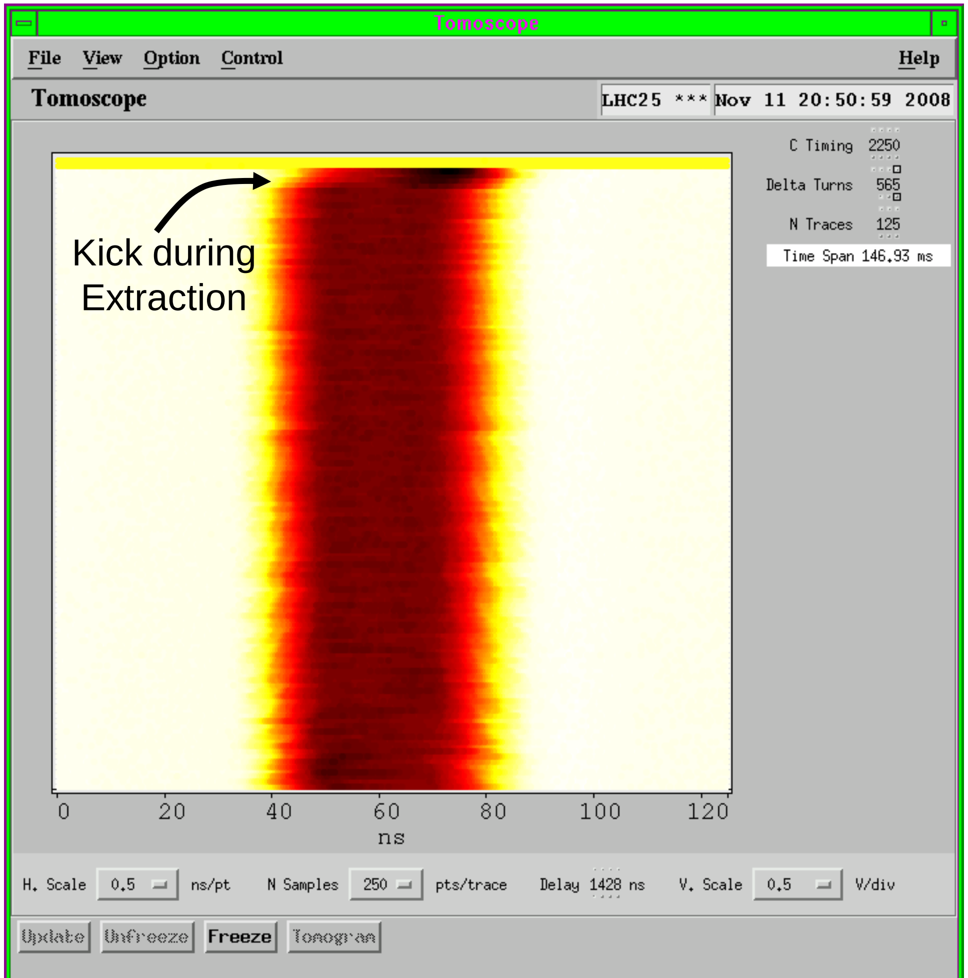


Became
more stable

☺

PS Flat bunch

V(h21)=31kV, V(h42)=16kV
, Dampers off



Flat bunch for about 145 msec at 26 GeV; quite stable (!!)

Prospects for LHC

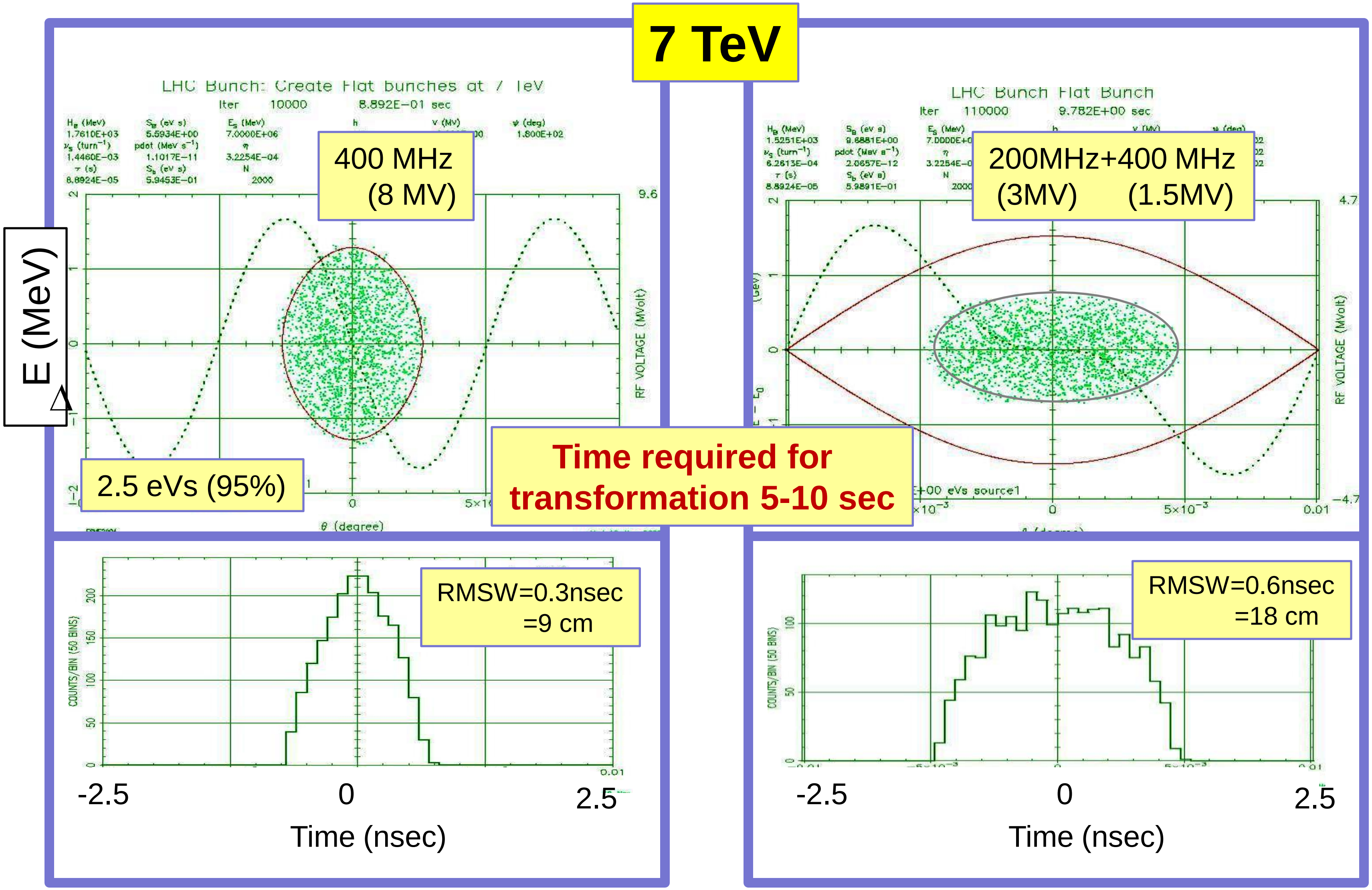
- There are two scenarios for flat bunches in the LHC using the 200 MHz (R. Losito et. al, EPAC2004, p956) and 400MHz RF systems in the Ring.
  - ❑ Create flat bunches at peak energy

    ← This can be implemented relatively soon
  - ❑ Create flat bunches at injection energy and accelerate to peak energy

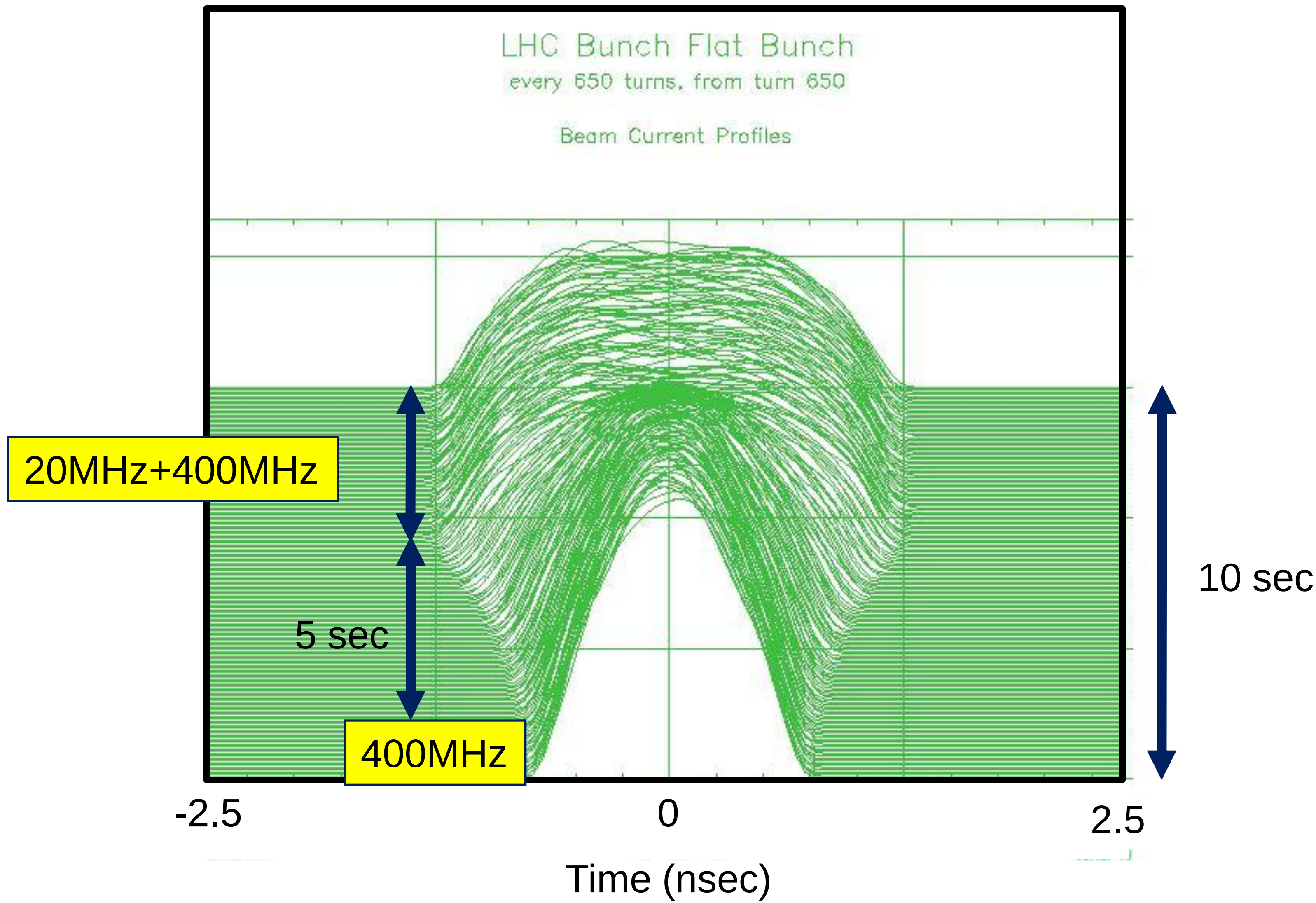
    ←This needs development of additional controls and a bit involved.

    ← But the advantage is that dp/p < 3 times smaller than that for normal acceleration case. We may be able to reduce beam losses significantly.

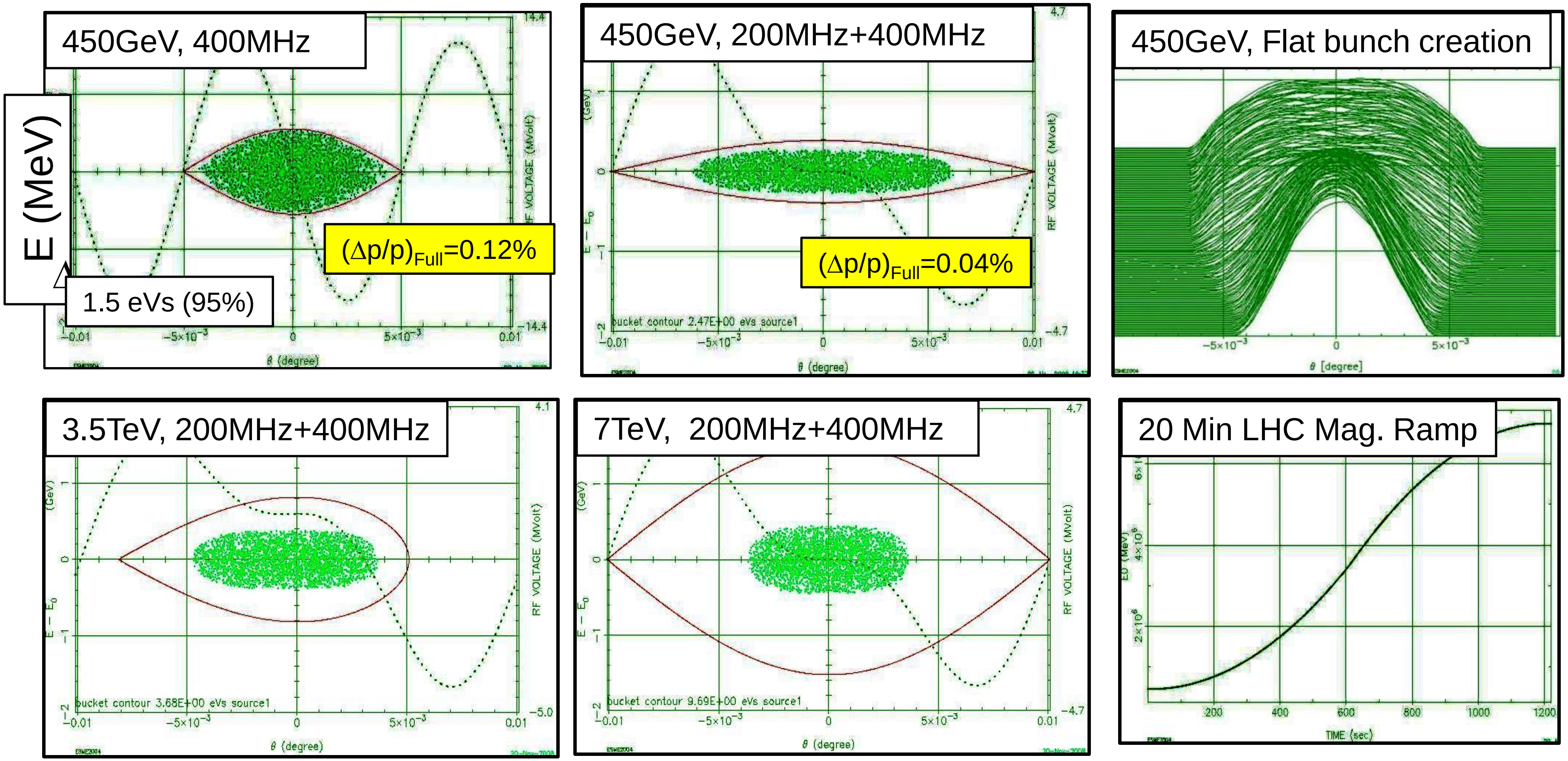
Evolution of RMSW of Bunches in LHC



Preparation of Flat Bunches at 7 TeV with 400MHz and 200 MHz rf systems



Flat Bunches at Injection & Acceleration using 400MHz and 200 MHz rf systems



Future prospects

Can LHC benefit from this scheme with nominal beam parameters?

Accelerator/ Storage Ring	frf MHz		Injection	Top Energy
Tevatron	53 MHz			
		E	150GeV	980GeV
		Vrf	1MV	1MV
		Bunch Area	2eVs	2.5 eVs
		Bkt.A/BA	2.1	4.2
LHC	400 MHz			
		E	450GeV	7000GeV
		Vrf	8MV	16MV
		Bunch Area	1eVs	2.5 eVs
		Bkt.A/BA	1.4	3.2
	200 MHz			
		E	450GeV	7000GeV
		Vrf	3MV	3MV
		Bunch Area	1eVs	2.5 eVs
		Bkt.A/BA	2.4	3.9

Larger Bkt.A/BA is always better

With 200 MHz and 400MHz rf system the bunches in LHC can be flattened. This implies

1. LHC luminosity increase of at least 30% for the same beam parameters
2. At least a factor of two less momentum spread for the beam. Hence, less beam loss around the ring.

Summary and Conclusions

- LHC luminosity can be increased by up to 40% (!!!) for the same number of particles/bunch and emittance, and other machine parameters by using flat bunches.
- I have presented here a discussion and simulation results on creation and acceleration of flat bunches in the LHC.
- Have carried out simulations and beam experiments to create flat bunches in the injectors (PS and SPS) to address beam instability issue
  - some preliminary analysis of the data from MD runs done and the results are promising
  - More studies to be undertaken next spring

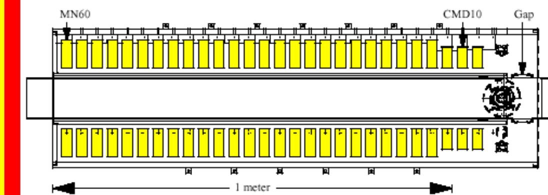
Flat bunch scenario for the LHC is a very promising path for the Luminosity upgrade

Barrier RF Systems

Barrier Cavities in the Recycler

Peak Voltage: 500V Power: 3.5kW
Type of Ferrite: Ceramic Magnetics MN60, CMD10
Shunt Impedance: 50 Ω /cavity
Band Width : 10kHz -100MHz
Dimension: ~ 1 meter
Cost: $75 k
Amplifier : Amplifier Research Model 3500A100
Cost: $150 k

PAC1999, p 869



Schematic drawing of Recycler Wideband RF Cavity

Peak RF Voltage: 500V
Type of Ferrite: Not Known
Shunt Impedance: 50Ω
Bandwidth ~50kHz-100MHz
Dimension= 1.5meter
Cost = not known

Main Injector Damper Cavities

Peak Voltage: 500V Power: 3.5kW
Type of Ferrite: 5 NiZn & 17MnZn Ferrite
Shunt Impedance: 50 Ω /cavity
Band Width : 10kHz -100MHz
Dimension: ~ 1 meter Cost: $75 k
Amplifier : Amplifier Research Model 3500A100
Cost: $150 k

D. Wildman
(private communications 2003)

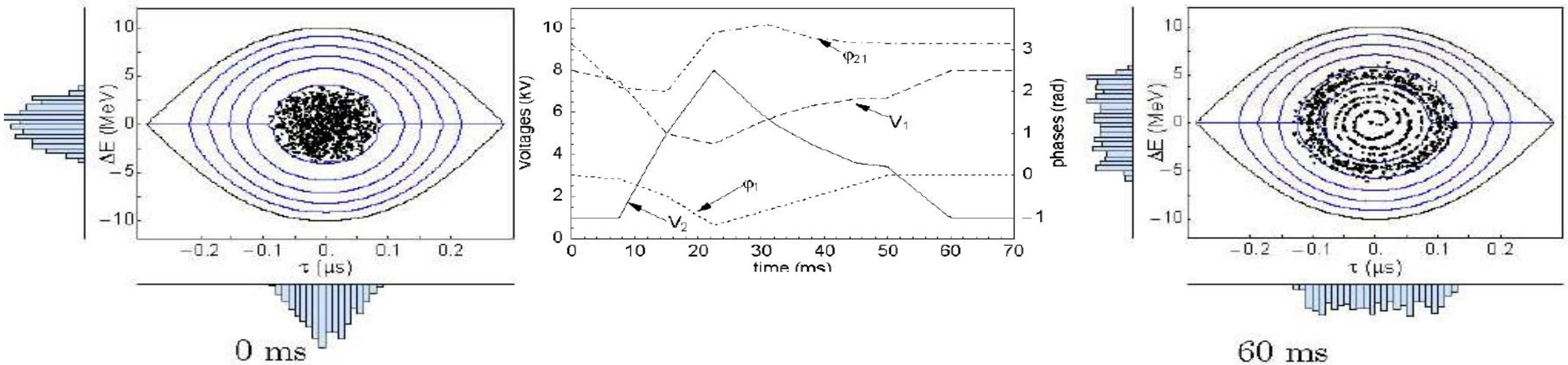
Main Injector Barrier Cavity

Peak Voltage: 10kV Power: 150kW
Type of Ferrite: 7 Finemet ® cores
Shunt Impedance: 500 Ω /cavity
Band Width : 50kHz -100MHz
Dimension: ~ 0.75meter Cost: $75 k
Amplifier : Switch
Cost: $40 k

D. Wildman
(private communications 2003)

Carli's Hollow Beam Technique
(EPAC2002, p233)
Simulations

Recombination with Empty Bucket



Redistribution of phase-space